

On minor black holes in galactic nuclei

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ABSTRACT

Small and intermediate mass black holes should be expected in galactic nuclei as a result of stellar evolution, minor mergers and gravitational dynamical friction. If these minor black holes accrete as X-ray binaries or ultra-luminous X-ray sources, and are associated with star formation, they could account for observations of many low luminosity AGN or LINERs. Accreting and inspiralling intermediate mass black holes could provide a crucial electromagnetic counterpart to strong gravitational wave signatures, allowing tests of strong gravity. Here we discuss observational signatures of minor black holes in galactic nuclei and we demonstrate that optical line ratios observed in LINERs or transition-type objects can be produced by an ionizing radiation field from ULXs. We conclude by discussing constraints from existing observations as well as candidates for future study.

Key words: galaxies: active – galaxies: individual – galaxies: LINERs – techniques: spectroscopic – X-rays: line – emission: accretion – disks :galaxies

1 INTRODUCTION

The largest black holes in the Universe live in the centers of galaxies (e.g. Kormendy & Richstone 1995). However, small to intermediate mass (or minor) black holes must also live in galactic nuclei as a result of stellar evolution, minor mergers and gravitational dynamical friction. This has two important consequences. First, some low luminosity galactic nuclei may not actually be powered by inefficient accretion onto a supermassive black hole. Instead, some galactic nuclei may be powered by a number of X-ray binaries (XRBs) or ultra-luminous X-ray sources (ULXs) possibly with some star formation around a quiet supermassive black hole (e.g. Ho 2008; McKernan et al. 2010). So, while accretion onto supermassive black holes can extend down to tiny fractions of Eddington luminosity (e.g. Ho 2008; Kauffmann & Heckman 2009), inferring very weak accretion rates becomes dangerous at low X-ray luminosities, since it is possible to get lost in the XRB or ULX nuclear noise. Second, inspiralling black holes offer an excellent opportunity to study strong gravity via gravitational radiation (e.g. Miller & Colbert 2004; Miller 2005). An X-ray counterpart to a source of gravitational radiation would be

extremely important since it would provide crucial simultaneous electromagnetic information about the predictions of strong gravity. Therefore we should investigate the occurrence of accreting, non-supermassive black holes in galactic nuclei.

In McKernan et al. (2010) we proposed that LINER 2s (LINERs devoid of broad H α wings) without flat-spectrum compact radio cores may be powered by nuclear ULXs and low levels of star formation, rather than low luminosity accretion onto supermassive black holes. Here we discuss the general phenomenon of minor black holes in galactic nuclei and observational consequences if they are accreting. In section §3.1 we discuss constraints on nuclear ULXs from BPT optical line ratio diagrams and simulated ULX continua. In section §3.2 we discuss constraints on the occurrence of nuclear ULXs (and XRBs) from existing observations. In section §3.3, we conclude by outlining future observational strategies in the X-ray, optical and IR bands to disentangle signatures of small mass black holes in galactic nuclei. We also point out that nuclear ULXs may be present in ‘transition’ type objects and that the presence of flat-spectrum compact radio cores need not rule out the presence of nuclear ULXs.

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2 SMALL & INTERMEDIATE MASS BLACK HOLES IN GALACTIC NUCLEI

The mass spectrum of astrophysical black holes in the Universe is believed to span around nine orders of magnitude. The largest, supermassive, black holes ($M_{BH} \sim 10^6 - 10^9 M_\odot$) live in galactic centers (e.g. Kormendy & Richstone 1995). X-ray observations of minor black holes ($\leq 10^5 M_\odot$) inevitably tend to be biased towards accreting black holes lying far from the centers of galaxies (e.g. Colbert & Ptak 2002; Miller & Colbert 2004; Winter et al. 2006). However, minor black holes must naturally occur in galactic nuclei as a result of stellar evolution ($M_{BH} \leq 20 M_\odot$) or minor mergers by clusters and dwarf galaxies ($10^2 \leq M_{BH} \leq 10^5 M_\odot$). In our own Galaxy, a large number of stellar mass black holes ($\sim 20,000$) are expected within $\sim 1\text{pc}$ of SgrA* (e.g. Morris 1993; Miralda-Escude & Gould 2000) and should dominate the mass density at $< 0.2\text{pc}$ (Freitag 2006). Munoz et al. (2005a) have found four X-ray transients within $\sim 1\text{pc}$ of Sgr A*, with (unobscured) peak X-ray luminosity $> 10^{36} \text{ erg s}^{-1}$ (Munoz et al. 2005b). Allied with evidence for young massive stars (3-7Myrs) within $\sim 1\text{pc}$ of SgrA*, this indicates that accreting minor black holes could be an important part of emission from galactic nuclei.

If minor black holes in galactic nuclei are accreting, their X-ray luminosities could mimic low luminosity AGN and LINERs and mis-classification of these galactic nuclei can occur. For example, in M82 an accreting black hole of mass ($500 M_\odot < M < 10^6 M_\odot$) yielding an X-ray luminosity of $L_x \sim 10^{40} \text{ erg s}^{-1}$, lies a mere $\sim 180\text{pc}$ from the kinematic center of the galaxy (Kaaret et al. 2001). The optical line ratios from the inner $\sim 200\text{pc}$ of M82 are consistent with a borderline H_{II} nucleus/transition object (Ho et al. 1997). If an identical galactic nucleus at $> 30\text{Mpc}$ were observed with Chandra (angular resolution $\geq 0.5''$), the X-ray emission would appear to originate in the galactic center and might incorrectly be thought due to inefficient accretion onto the central supermassive black hole. Likewise, in M31 there are 33 X-ray point sources in the innermost $\sim 450\text{pc}$ of that galaxy, with individual luminosities spanning $L_x \sim [10^{36}, 10^{38}] \text{ erg s}^{-1}$ (Kong et al. 2002). If an identical galactic nucleus at $\sim 100\text{Mpc}$ were observed with Chandra, it would have a nuclear X-ray luminosity of $L_x \sim 10^{39} \text{ erg s}^{-1}$, comparable to that of some LINERs.

Studies of nearby galaxies, such as M81 ($\sim 3.9\text{Mpc}$, 124 X-ray sources, (Swartz et al. 2003)), M83 ($\sim 4\text{Mpc}$, 81 X-ray sources (Soria & Wu 2002)) and M101 ($\sim 7\text{Mpc}$, 110 X-ray sources (Pence et al. 2001)) encourage us to expect (at the very least) multiple moderate luminosity X-ray sources in most galactic nuclei. In actively star forming galaxies, such as The Antennae (NGC 4038/39) at $\sim 19\text{Mpc}$, there are nine ULXs with $> 10^{39} \text{ erg s}^{-1}$ (Fabbiano et al. 2001). X-ray luminosity functions (XLFs) can help to disentangle sources of X-ray emission in galactic nuclei (e.g. Kim & Fabbiano 2004). In M31 large difference in XLFs between the inner bulge, outer bulge and disk X-ray point source populations may be due to limited statistics, differences in stellar ages, or contributions from globular clusters (e.g. Kong et al. 2002; Williams et al. 2004; Kim & Fabbiano 2004). Furthermore, since X-ray transients can actually dominate XLFs (Piro & Bildsten 2002), the

treatment of transient outbursts can make a big difference in expected XLFs (Fragos et al. 2008).

The orbits of minor black holes in galactic nuclei will tend to decay via gravitational dynamical friction (e.g. Madau & Rees 2001; Miller & Colbert 2004). So minor black holes will tend to migrate deeper into galactic nuclei over time. The dynamical frictional time (t_{fric}) for an object of mass M at galactic radius r , to sink to the galactic center (with central velocity dispersion σ) is given by

$$t_{fric} = \frac{5 \times 10^9 \text{ yrs}}{\ln \Lambda} \left(\frac{r}{\text{kpc}} \right)^2 \frac{\sigma}{200 \text{ km/s}} \left(\frac{M}{10^7 M_\odot} \right)^{-1} \quad (1)$$

where $\ln \Lambda \sim 5 - 20$ is the Coulomb logarithm (e.g. Miller & Colbert 2004) and a smooth, homogeneous background is assumed. Note that this assumption may break down inside $\sim 10\text{pc}$, but we ignore this for simplicity as it does not affect our general argument. Figure 1 shows the distance of minor black holes from a central supermassive black hole as a function of redshift (or time). Frictional timescales are calculated from equation 1 assuming $\ln \Lambda \sim 10$ and $\sigma \sim 200 \text{ km s}^{-1}$. Solid curves indicate black holes of mass $10, 10^2, 10^4, 10^6 M_\odot$ formed or introduced by merger at $z \sim 2$. Dashed and dotted curves correspond to the inspiral of a $10 M_\odot$ black hole formed at $z = 0.5$ and $z = 0.1$ respectively. Filled-in circles on the $10 M_\odot$ curves correspond to examples of binary companion main sequence lifetimes. Vertical dashed lines in Fig. 1 correspond to the limiting angular resolution of $\sim 0.5''$ on Chandra at 1, 10 and 100Mpc respectively. Thus, for example a $10 M_\odot$ black hole born $\sim 1\text{pc}$ from the central supermassive black hole at $z \sim 0.1$ will merge with the central black hole around $z \sim 0.06$ and could be fuelled during the entire inspiral by a binary companion with a mass corresponding to spectral class A0 or lower. While $\sim 1\text{pc}$ seems particularly close to the central black hole for star formation/evolution, in our own Galaxy tens of O and B stars can be found $0.01 - 5\text{pc}$ from the supermassive black hole (Perets & Gualandris 2010). In Fig. 1 the main sequence lifetime of binary companions is likely to be the limiting factor for fuelling stellar mass black holes ($\leq 20 M_\odot$), assuming $\sim 1\%$ Eddington accretion and either continuous accretion from O/B companions or sporadic outbursts from lower mass companions, as observed in our own Galaxy (Remillard & McClintock 2006). For black holes much larger than stellar mass, gravitational capture of companions is the more likely fuelling scenario, particularly with increasing mass, but this is difficult to model appropriately. Nevertheless, some fraction of IMBHs must capture companions during their inspiral.

3 WHERE SHOULD WE LOOK?

While several accreting black holes should be expected in most galactic nuclei, it should be easier to isolate them in certain kinds of nuclei. In McKernan et al. (2010), we suggested that certain types of LINER nuclei may in fact be powered by nuclear ULXs or XRBs. Evidently, if objects such as M82 and M31 were observed from large distances, they would look similar in the X-ray band to low luminosity AGN and LINERs observed at these distances (e.g. Gonzalez-Martin et al. 2009). But what about the optical

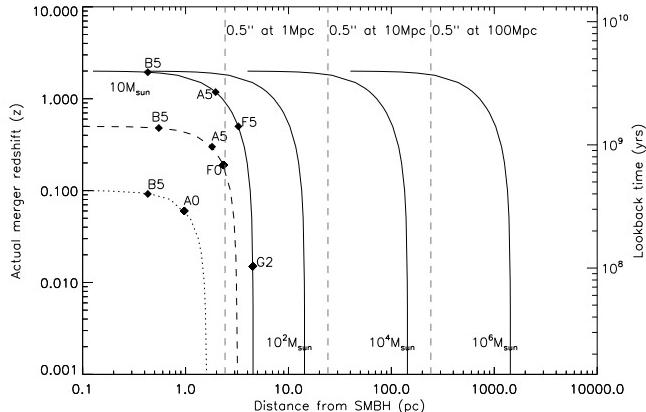


Figure 1. Distance of minor black hole from galactic center as a function of redshift (left y-axis) and time (right y-axis). Solid curves correspond to minor black holes of mass $10, 10^2, 10^4, 10^6 M_{\odot}$ formed or introduced by minor merger at a redshift of $z = 2$. Depending on the initial distance (x-axis) at $z = 2$, the redshift at which the merger occurs lies between $z \sim 2$ and $z \sim 10^{-3}$. Dashed and dotted curves correspond to inspiralling $10 M_{\odot}$ black holes introduced at $z = 0.5$ and $z = 0.1$ respectively. Vertical dashed lines correspond to Chandra's limiting angular resolution of $0.5''$ at 1, 10 and 100 Mpc (left to right) respectively. Filled-in diamonds on $10 M_{\odot}$ curves correspond to example binary companion main sequence lifetimes. Curves may be read as follows: A $10 M_{\odot}$ black hole that forms e.g. $\sim 2(4)$ pc from the central supermassive black hole at $z = 2$ will merge at $z \sim 1(0.2)$. An A5(F5) companion would not last long enough to fuel accretion during the entire inspiral to $z = 1(0.2)$, but a companion of mass G2 or lower could last this long.

emission lines from these nuclei? In the optical band, diagnostic diagrams, using common, low-ionization lines are used to separate galactic nuclei according to classification (e.g. Veilleux & Osterbrock 1987; Kewley et al. 2001, 2006). For Seyfert AGN, the ionization parameter spans a wide range and can be very high (e.g. McKernan et al. 2007), placing AGN in the upper right section of diagnostic diagrams. LINERs lie below and to the right of a theoretical mixing line, in a region where shocks or a power-law ionizing radiation field with low ionization parameter can yield the appropriate optical line ratios (see e.g. Kewley et al. 2006). A nucleus powered by ULXs or multiple XRBs could have a low ionization parameter, but a relatively hard (X-ray dominated) radiation field which could drive optical line ratios into the 'LINER' section of a diagnostic diagram, even though the central supermassive black hole is quiescent. Low luminosity galactic nuclei may therefore be fruitful places to search for minor nuclear black holes.

3.1 Simulated ULXs powering LINERs

In McKernan et al. (2010) we suggested that nuclear ULXs could power certain ('radio quiet') LINER 2s. In order to investigate the LINER 2 population, we extracted all the LINER 2 (L2) and transition 2 (T2) objects from the Palomar sample of Ho et al. (1997). We included T2 objects since they occupy the same 'LINER' region of diagnostic diagrams. Figure 2 shows the optical diagnostic diagram of

$[O_{III}]/H_{\beta}$ vs $[O_I]/H_{\alpha}$ for these objects, where L2s are denoted by crosses and T2s by open circles. Where radio data is available, we have superimposed symbols on some of these objects. The blue, downward pointing triangles correspond to L2 and T2 objects *without* flat-spectrum radio cores (or 'radio quiet'). Black, upward pointing triangles denote L2 and T2 objects *with* flat-spectrum radio cores. The red curve corresponds to the starburst limit curve and the blue dashed line corresponds to the extreme mixing line (separating AGN and LINERs) (Kewley et al. 2001, 2006). Corresponding diagrams for $[N_{II}]/H_{\alpha}$ and $[S_{II}]/H_{\alpha}$ look similar to Fig. 2 (see also Ho (2008)). Interestingly, the only distinction between the 'radio quiet' and 'radio loud' populations of L2 and T2 objects seems to be that the radio quiet objects have $[O_I]/H_{\alpha} < 0.2$, implying FUV continuum penetrating relatively dense material, suggestive of star formation. Kewley et al. (2006) show that the optical line ratios for most LINERs could be produced by a 'mean' AGN SED with $\log U \leq -3$ and slightly harder ionizing radiation fields.

To investigate the possibility that ULXs or XRBs with $\log U \sim -3.0$ could push line ratios out of the starburst region and into the transition/LINER region of the optical diagnostic diagrams, we ran simulations with CLOUDY v8.0, described by Ferland et al. (1998). For the ULX continuum, we used X-ray band continuum values from the observational study of ULX populations in nearby galaxies in Winter et al. (2006). In this study, spectra of all the brightest X-ray sources were extracted from a sample of 32 galaxies. ULX spectra were categorized based on their luminosity and spectral shape into 'low-hard' state sources, with an average power-law index of $\Gamma = 2.1$, and 'soft-high' state sources, with a power-law index of $\Gamma = 2.5$ plus a blackbody with temperatures in the range [0.1, 1] keV. In AGN, the $[O_{III}]$ line strength requires a compact narrow line region, moderate density ($\sim 10^3 \text{ cm}^{-3}$) and a moderate covering fraction (0.02-0.2) (Baskin & Laor 2005), so we used these values as a guide. Therefore, our ULX continuum radiation was chosen to ionize a sphere of material with a filling factor of 10% and a density of $\sim 10^3 \text{ cm}^{-3}$ located at $10^{17} - 10^{17.5} \text{ cm}$ from the continuum source. This corresponds to $\log(N_H) = 20.3$ which is less than the fiducial $\log(N_H) = 21$ for NLR clouds. The powerlaw continuum was assumed to span 1-1000 Ryd (unless otherwise specified) and the powerlaw and blackbody in the 'soft-high' state were assumed to have identical ionization parameters such that total $\log U = -3.0$. Note that a wide range of ionization parameter ($\log U$) is likely for ULXs since this depends on a wide range of parameters (such as the density and location of ionized material, the nature of the black hole accretion and outflows). Since ULXs are comparably bright to low luminosity AGN in X-rays, we simply chose a value of $\log U$ appropriate to low luminosity AGN. Future simulations will be required to understand the dependence of line ratios on a variable $\log U$. In Fig. 2 the dashed (interpolated) curve corresponds to simulated line ratios produced by the 'low-hard' ULX spectrum, and filled-in points along the curve correspond to a power-law continuum spanning (from left to right) 1, 1.5, 2, 5, 10-1000 Ryd. The shorter solid (interpolated) curve in Fig. 2 corresponds to simulated line ratios due to a 'soft-high' ULX ionizing continuum, where filled-in points correspond to a blackbody at temperature (from left to right), $10, 5, 2 \times 10^6 \text{ K}$.

The first point to make from Fig. 2 is that simulated ULX continua seem perfectly capable of generating optical line ratios observed in transition-type objects and LINERs. The ULX ionizing continuum must include some FUV ($\sim 1 - 10$ Ryd) in order to produce $[O_I]/H_\alpha$ ratios in the correct range, but apart from this the simulated line ratios do not depend very strongly on the continuum shape. The second point from Fig. 2 is that ULX black hole mass can determine whether the optical line ratio is transition-like or LINER-like. For example, a blackbody temperature of 5×10^6 K, corresponds to emission from an accretion disk around a $\sim 10M_\odot$ black hole accreting near Eddington luminosity and generates a line ratio (middle point on solid curve) in the middle of the transition object region. By contrast, a blackbody temperature of 2×10^6 K corresponds to an accretion disk around a $\sim 10^3 M_\odot$ black hole and generates a line ratio (rightmost point on solid curve) in the LINER region. From Fig. 2, the 'radio quiet' L2 and T2s have $[O_I]/H_\alpha < 0.2$, so if they are powered by 'soft-high' state ULXs as we suggested in McKernan et al. (2010), the black hole masses must be $< 10^3 M_\odot$ and some FUV continuum is required (possibly from star formation). We will carry out more detailed simulations in the future to understand the limits on optical line ratios for different values of $\log U$, the absorbing column and different ionizing continua, nevertheless for the purposes of this Letter, ULXs can in principle generate optical line ratios observed in LINER and transition-type nuclei.

3.2 Observational Constraints

Recently Gonzalez-Martin et al. (2009) claimed that nuclear X-ray emission in LINERs could not be due to high mass XRBs since populations of young stars in these nuclei are generally ruled out. Of course, as discussed above, it is not necessary to have populations of young stars to account for X-ray observations of low luminosity galactic nuclei. Ptak et al. (2006) find that X-ray/optical flux ratios for optical counterparts to ULXs are generally consistent with LMXB in *old* clusters. Furthermore, in M31, the distribution of variable X-ray point sources in the innermost ~ 450 pc may be consistent with an ageing population of low mass XRBs (Kaaret 2002). Therefore, integrating over the contributions from low mass XRBs is perfectly capable of powering nuclear X-ray emission for Gyrs and potentially generating a LINER-like or transition object-like appearance. Although low mass XRBs tend to be transient, they can actually dominate the XLF with reasonable choice of duty cycles (Piro & Bildsten 2002). For example, a choice of outburst rate (O.R.) $\sim 10\%$ during $\sim 75\%$ of the lifetime of XRBs is a reasonable estimate for the nucleus of Cen A (Piro & Bildsten 2002). Munoz et al. (2005a) suggest O.R. $\sim 1\%$ for an estimated population of $\sim 10 - 10^3$ binaries within < 1 pc of SgrA* could account for XRT observations. ULXs if unbeammed could have duty cycles as high as $\sim 10\%$ (King et al. 2001).

We should expect (at least) several low mass XRBs in $\sim 0.5 - 1''$ X-ray observations of most galactic nuclei. Nuclear ULXs, like that in M82 should occur with moderate levels of star formation in the nucleus, although ULXs are observed in early-type galaxies at a rate of a few per galaxy (e.g. Fabbiano & White 2003). Indeed the mass of the ULX in M82 suggests that it is cannibalizing its host cluster or

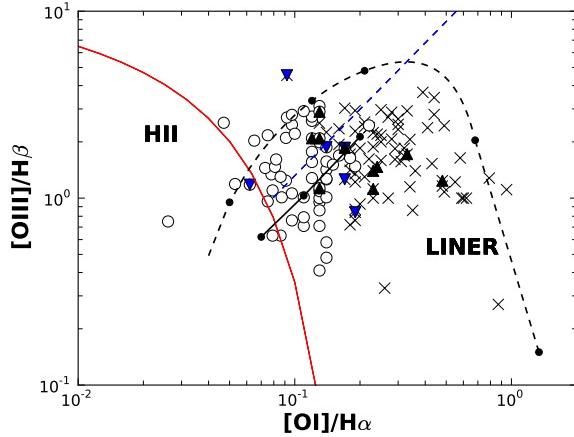


Figure 2. Plot of $[O_{III}]/H\beta$ vs $[O_I]/H\alpha$ for all L2(crosses) and T2 objects (open circles) in the sample of (Ho et al. 1997). Highlighted are those objects (both L2 and T2) with (filled-in blue triangles pointing down) and without (filled-in black triangles) compact, flat-spectrum radio cores. Dashed line denotes simulated optical line ratios from a 'low-hard' ULX continuum (from Winter et al. (2006)), with the filled-in points on this curve corresponding to continuum starting energies of 1, 1.5, 2, 5 and 10 Ryd from left to right respectively (see text for details). The solid curve corresponds to a 'soft-high' ULX continuum (from Winter et al. (2006)), with the filled-in points corresponding to (from left to right) blackbody temperatures of $10, 5, 2 \times 10^6$ K respectively (see text for details).

has captured companions. Another possible inconsistency between LINER X-ray emission and ULX or XRB emission is the XLF of LINER nuclei (Gonzalez-Martin et al. 2009). However, the sample size (82) of Gonzalez-Martin et al. (2009) is limited (see (Kim & Fabbiano 2004) for discussion of the dangers of this). Furthermore, their cumulative power-law indices ($\sim -0.2, -0.8$) before and after the power-law break are actually not that different from the *cumulative* power-law indices of XRBs at low luminosities (~ -0.8) in (Kim & Fabbiano 2004) or even from M31 (Kong et al. 2002), although these steepen at higher luminosities. A much larger LINER sample is evidently required for a reliable understanding of the LINER XLF.

The UV band is important in our discussion, since emission from an accretion disk around supermassive black holes should peak in the UV band. Maoz et al (2005) found evidence for UV variability in LINER 1s and LINER 2s. However of the five LINER 2s in Maoz et al (2005) without a compact radio core, none varied at $> 95\%$ confidence and three of the five radio-quiet LINER 2s (NGC 3486, NGC 4569 and NGC 5055 at 9, 1 and 8 Mpc distant respectively) were consistent with no UV variation whatsoever (Maoz et al 2005). This suggests that hot stars rather than AGN are powering the UV emission in radio-quiet LINER 2s. X-ray imaging of LINERs reveals that extended emission or complex clumpy emission is common in LINER 2 nuclei. Extended emission can be explained in a nuclear ULX model by several ULXs/XRBs in a nucleus, in a region of hot massive stars. In a small sample of L2 and T2 nuclei, around half showed clear evidence for extended emission (Terashima et al. 2002). Extended emission may

be present in the other L2 and T2 nuclei in the sample of Terashima et al. (2002) but these objects are faint.

3.3 Future Observational Constraints

Several observational approaches can be taken to isolate emission from minor black holes in L2 and T2 galactic nuclei. In the X-ray band, high angular resolution imaging and timing studies of nearby L2 and T2 nuclei will put limits on the number and accretion rate of candidate ULXs. In the optical band, variation in the optical line ratios of L2 and T2 nuclei will determine whether the source of the ionizing radiation is varying rapidly. Also in the optical band, high angular resolution studies of these nuclei will allow us to identify possible counterparts to sources of nuclear X-ray emission (for example, a nuclear globular cluster containing an accreting IMBH). In the IR band, high angular resolution images will identify star forming regions and their proximity to nuclear X-ray sources, as well as putting limits on reprocessed ionizing radiation that could originate from ULXs.

In this letter we have emphasized searches for accreting minor black holes in galactic nuclei without flat-spectrum radio cores. However, we note that stellar mass black holes also show evidence for radio jets, with flat or steep spectra depending on their X-ray state (e.g. Corbel et al. 2001). Radio jets may also be associated with these ULXs (e.g. Georganopoulos et al. 2002; Kaaret et al. 2003). So, some L2s and T2s with flat-spectrum radio jets may also be powered by ULXs, although this is beyond the scope of the present work. Finally, we briefly note that while X-ray bright accretion onto the central supermassive black hole will drown out emission from nearby minor black holes, signatures of minor black holes could still show up. Signatures might include a break in the nuclear X-ray luminosity function, a soft X-ray excess that varies on much faster timescales than the rest of the X-ray continuum and characteristic breaks in the power spectral density of the nucleus.

4 CONCLUSIONS

We should expect large numbers of minor black holes in galactic nuclei as a consequence of stellar evolution, minor mergers and gravitational dynamical friction. If the central supermassive black hole is relatively quiescent, actively accreting minor black holes could dominate the nuclear X-ray emission. This could result in the mis-classification of LINER and transition-type activity in galactic nuclei. Furthermore, inspiralling minor black holes could be important sources of gravitational radiation and if accreting, could be very useful in studying predictions of strong gravity. Here we show that nuclear ULXs are capable of producing the optical line ratios observed in LINER and transition-type objects. If nuclear ULXs are responsible for the activity in radio-quiet LINER 2 nuclei, as suggested in McKernan et al. (2010), preliminary simulations indicate that the ionizing continuum is likely to be 'soft-high' and originating from around black holes with mass $< 10^3 M_\odot$. We outline some future observational strategies to constrain emission from minor black holes in galactic nuclei.

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6 *B. McKernan, K.E.S. Ford, T. Yaqoob & L.M. Winter*

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